Multiphase Transformer Modelling using Finite Element Method

By Tole Sutikno

International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 6, No. 1, March 2015, pp. 56~64
ISSN: 2088-8694

Multiphase Transformer Modelling using Finite Element Method

Nor Azizah Mohd Yusoff*, Kasrul Abdul Karim*, Sharin Ab Ghani*, Tole Sutikno, Auzani Jidin***
* Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malacca, Malaysia
** Departement of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

Article Info

Article history:

Received Nov 10, 2014
Revised Dec 22, 2014
Accepted Jan 5, 2015

Keyword:

Finite element
Five-phase motor
Multiphase
Three-phase supply
Transformer

ABSTRACT

In the year of 1970 saw the starting invention of the five-phase motor as the milestone in advanced electric motor. Through the years, there are many researchers, which passionately worked towards developing for multiphase drive system. They developed a static transformation system to obtain a multiphase supply from the available three-phase supply. This idea gives an influence for further development in electric machines as an example; an efficient solution for bulk power transfer. This paper highlighted the detail descriptions that lead to five-phase supply with fixed voltage and frequency by using Finite-Element Method (FEM). Identifying of specification on a real transformer had been done before applied into software modeling. Therefore, Finite-Element Method provides clearly understandable in terms of visualize the geometry modeling, connection scheme and output waveform.

Corresponding Author:

Nor Azizah Mohd Yusoff,
Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka (UTeM),
76100 Durian Tunggal, Malacca, Malaysia.
Email: kasrul@utem.edu.my

1. INTRODUCTION

Multiphase (more than three-phase) system has been the focus of research recently due to their intrinsic advantages compared to three-phase systems. The applications of multiphase systems are investigated to be in electric power generation, transmission, and utilization. Six phase transmission lines can provide the same power capacity with a lower phase-to-phase voltage and smaller, more compact towers compared to a standard double-circuit three-phase line. The geometry of the six-phase compact towers may also aid in the reduction of magnetic fields as well [1]-[4]. The multiphase motors are typically supplied by ac/dc/ac converters. Hence, the focus of the research on the multiphase electric drive is limited to the modeling and control of the supply systems. As three-phase supply is directly available from the grid, there's need to develop a fixed phase transformation system to obtain a multi-phase supply from existing three-phase supply [5].

This paper literally proposed a continuous study of the phase transformation system whereby using available three-phase supply transform into multi-phase supply develop from the static phase transformation system. Transformer is becoming a key instrument in the development of five-phase supply via special transformer connection technique. This concept has recently been challenged by transformer studies demonstrating their working mechanism and its different variants. Part of the aim of this project is to develop a five-phase transformer operating system that is compatible using Finite-Element Method through ANSYS MAXWELL 3D software. Basic block diagram for the system is shown in Figure 1. By using Finite-Element tools, three single-phase transformers model have been developed according to actual specification. These models then can be driven by various connection schemes of the circuit (Star-Star, Star-Polygon, Delta-Star or Delta-Polygon). Minimize the scope, this paper focused on the star-star connection scheme. Finite-element method, (FEM) techniques are useful to obtain an accurate characterization of the electromagnetic behavior of the magnetic components, such as transformer. Then, the main advantages of the FEM over the other methods because its ability to sketch model of transformer in geometrically and solve compositionally complex problems [6]. In fact, it is capable to take into account the non-linearity and inhomogeneous characteristic of the model [7]. Hence, it resulting a good approximation to the actual transformer model. Moreover, the transient model coupled with external circuit, allows user to simulate the dynamic behavior of the transformer with the real power supply and external load connection. This paper starts with a detailed description of Multiphase concept and connection scheme in section 2. The number of turn for each core was estimated accordingly. In section 3 described the design data based on the actual transformer. All this data will be employed to create the model of transformer using FEM in section 4. In FEM, the model has typically been coupled to circuit simulation using ANSYS Circuit Editor. This approach can be very accurate, but with long duration of time taking for simulation. The result from FEM will be shown in this section. It was clearly seen that the output is a balanced five-phase supply converting from a balanced three-phase input.

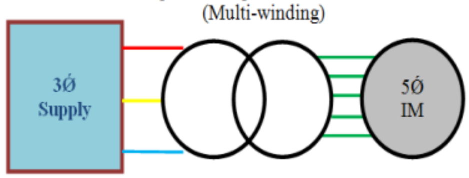


Figure 1. Block representation of the Multiphase system

2. RESEARCH METHOD

This section presented the technique to obtain of five phase as illustrated in Figure 3, Figure 4, Table 1, and Table 2. The phase voltages are all equal in magnitude but only differ in their output phase angle, which required for phase angle 72^{o} between each phase. The construction for output phase is found using appropriate turns ratio from the principal of phasor diagram. The turn ratios of a transformer are defined as the number of turns on its primary devided by the number of turns on its secondary. The turns ratio of a transformer therefore defines the transformer as step-up or step-down. However, almost every paper that has been written on multiphase transformer includes a section relating to turns ratio used 1:1 of turns ratio. Under this condition, the ratio of the input to output voltages would be equal as in equation (1) where a is defined the turn ratio of the transformer. By examining the simulation graph in Figure 11 and 12, the output of the three phase transformer in 20V after transforming from three phase to five phase the output is also remaining as 20V.

$$\frac{E1}{E2} = \frac{N1}{N2} = a \quad (1)$$

Figure 2 below summarizes all necessary steps for creating a Multiphase of power Transformer:

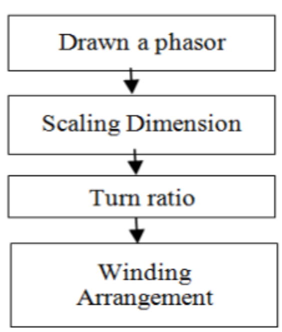


Figure 2. Modeling process of Multiphase Transformer

The phasor diagram for multiphase is drawn manually from AutoCAD. The correct use of AutoCADs dimension is the key to producing consice measured drawings. To measure turns ratio, the measurement of dimension lines phasor was used.The diagram in Figure 4 represents the winding arrangement in order to develop a Multiphase system.

2.1. Phasor Diagram Construction

In the transformer modeling the input phases are indicated with letters “X”, “Y”, and “Z” refer specifically to the red, yellow and blue color while the output phases are indicated with letters “A”, “B”, “C”, “D” and “E” correspond to the green color as illustrated in Figure 2 of phasor diagram.

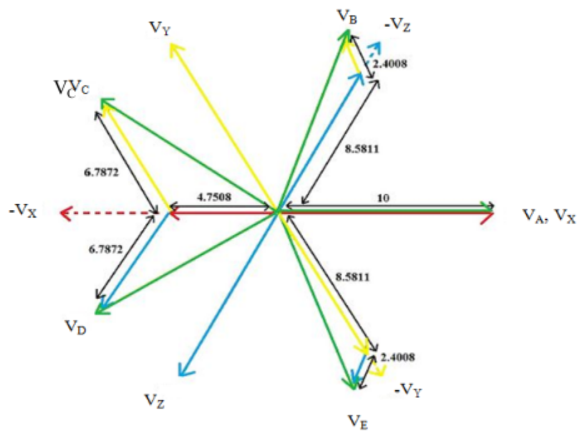


Figure 3. Phasor representation of the Multiphase transformer connection

The turn ratios will be determined through phasor scaling. This process can be done mathematically by ruling the length of the diagonal line or their magnitude from zero point. For example output phase “A” (V_A) is along with input phase “X” (V_X). Next, the output phase for “B” (V_B) will be determined through vector addition of two voltages which involves by forming a triangle. So, the components for output phase “B” can be formed by adding two vectors ($-V_Z + V_Y$). Similarly, “C” (V_C) is obtained from vector ($-V_X + V_Y$). The output of phase “D” (V_D) is obtained by the vector addition of voltage in ($-V_X + V_Z$) and last but not least the output phase “E” (V_E) is from the vector sum of voltage ($-V_Y + V_Z$). In this way the five phases are obtained from three phase to five phase. Yet, it may produce an error if not drawn phasor diagram accurately or correctly to scale. So, the number of turn can be calculated by applying the formula proposed given in Equation (3) with initial number of turn for primary winding are acquire from Faraday’s law equation in (2).

$$\mathrm{Np} = \frac{V}{4.44 f \Phi_{max} A_{Bobbin}} \qquad (2)$$

Where:
V = RMS value
f = frequency of the flux
N_P = Number of turns on the primary winding
Φ_{max}= Peak value of the flux
A = area of bobbin
4.44 = a constant [exact value = $2\pi/\sqrt{2}$]

Table 1 and 2 shows the number of turn for primary and secondary of transformer using in modeling by following the proposed equation below.

$$\frac{Length\ of\ the\ line\ (magnitude)}{10} \times N_P = Number\ of\ Turn \qquad (3)$$

Table 1. Turn ratio for Primary turns.

Primary	*Length (Voltage Magnitude, V)*	**Turns, N**
X	10	200
Y	10	200
Z	10	200

Table 2. Turn ratio for Secondary turns.

Secondary	*Length(Voltage Magnitude, V)*	*Turns, N*
X	10	200
	4.7508	95
Y	2.4008	48
	6.7872	136
	8.5811	172
Z	2.4008	48
	6.7872	136
	8.5811	172

2.2. Winding Connection Scheme; star-star

In line with Table 1 and Table 2 can be seen for Multiphase system, three single phase transformers are needed (X, Y, and Z). In each core carrying one primary and three secondary coils, except in core 'x' which only two secondary coils are used. Thus, this entire transformer consists of six terminal of primaries (V_X, V_Y and V_Z) and 16 terminals of secondary (V_A, V_B, V_C, V_D and V_E). The terminal from entire transformer will be connected in star-star connection.

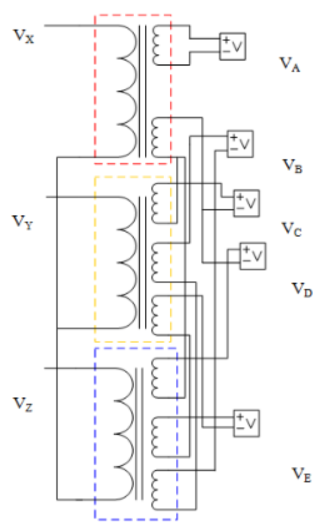


Figure 4. Winding arrangement of five phase transformer

3. MODEL DETAIL

Simulations from FEM were carried out based on custom build of single phase, shell-type transformer. Shell form is characterized by the winding wrapped central to the three-legged of E and I laminated core. Figure 5 shows the physical sketch dimension of magnetic core:

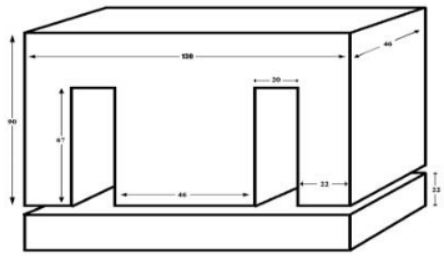


Figure 5. Core Dimension

The window of core will determine the amount of copper that appears in the window area of transformer. These entire factors are added together; total about 80 percent from the whole window core area (Figure 6). The window utilization will be influenced by five factors which is:

a) Insulation of wire
b) Fill factor
c) Effective window area (or when using a toroid, the clearance hole for passage shuttle)
d) Insulation required for multiplayer windings, or between windings
e) Workmanship, (quality)

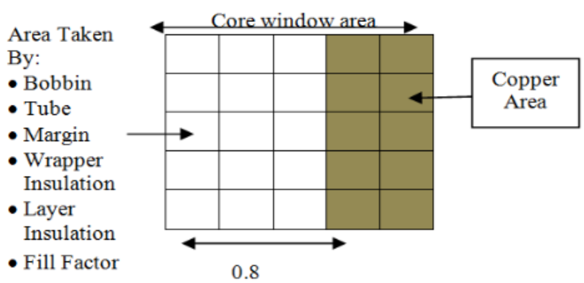


Figure 6. Window areas for copper

By employing the Equation (2) and (3), data were gathered and given as in Table 3. Hence, the diameter of the wire is then be determined by transformer window size accordingly to the highest number of windings. By referring to the table, core 'y' and core 'z' has the highest value of 556 turns.

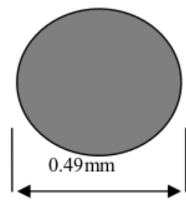
Table 3. Total number of winding for each core

Core / *Winding*	*X*	*Y*	*Z*
Primary 1	200	200	200
Secondary 1	200	48	48
Secondary 2	95	136	136
Secondary 3	-	172	172
Total	**495**	**556**	**556**

Diameter of wire can be determined using the Equation (4):

$$d^2 = \frac{A_{Core\ window}}{maximum\ turns} \quad (4)$$

$$A_{core\ window} = 67\text{mm x } 20\text{mm}$$
$$= 134\ \text{mm}^2$$
$$d^2 = 0.8 \times \frac{134mm^2}{556}$$
$$= 0.241\text{mm}^2$$
$$d = \sqrt{0.0241}$$
$$= 0.49\text{mm} / 24 \text{ gauge (AWG)}$$



4. FEM SIMULATION RESULT

Multiphase systems of transformer in FEM working under transient analysis can be devided into two main parts: Geometrically model and export the external circuit connection in Maxwell 3D. Further data collection is required to analyze the model with the electromagnetic behavior implemented within the Magnetostatic solver.

4.1. Transformer Model using FEM

The first stage of the simulation is starts with sketch the geometry model for three single phase transformer by Finite Element Method (FEM). Figure 7 and Figure 8 shown the normal transformer was modelled both in 3D and 2D FEM. The primary winding and secondary windings are represent by rectangles of corresponding material in Table 4. The insulation between turns and layers can be ignored completely. To enable the five-phase output can be seen clearly, the software was carried out with certain analysis setup. The sheet windings were assigning with coil terminal using the data from Table 3. Finally, the solution setup for the parameters used for solving the simulation has to be specified.The transformer assembly is composed of multiple materials and their model details are listed in Table 4.

Table 4. Details of Transformer Model Specification

Classification	*Specification*
Voltage [V]	20
Frequency [Hz]	50
Core Material	Steel 1008
Winding Material	Copper

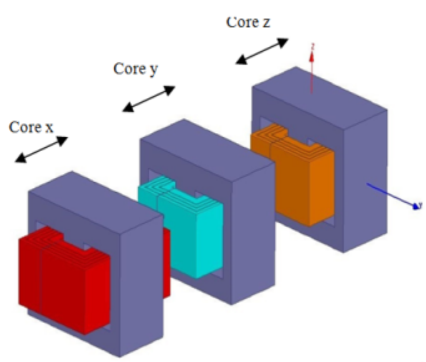


Figure 7. 3D model of transformer in FEM

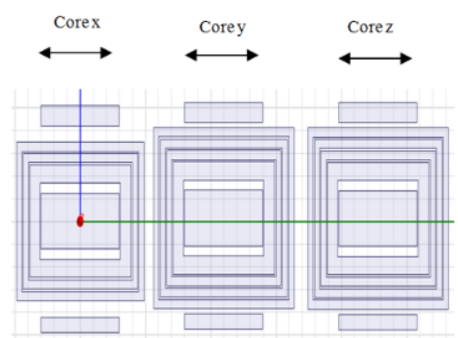


Figure 8. 2D model of transformer in FEM

4.2. Circuit-coupled Connection

The transient model coupled with external circuit based on Figure 4 connection scheme. The windings from finite element model are driven by this external circuit (Figure 10) in star-star circumstance.

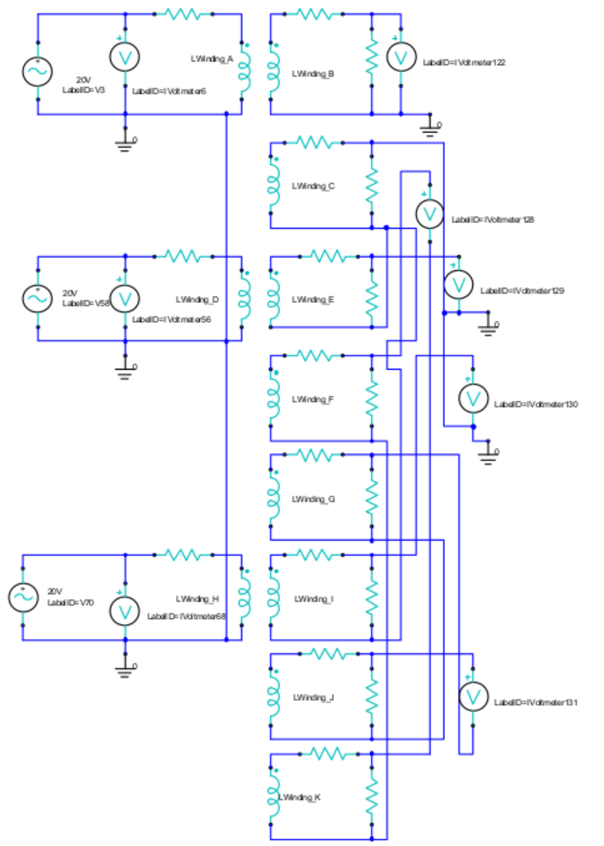


Figure 9. Transformer connection scheme from ANSYS Maxweel Circuit Editor

4.3. Magnetic Flux Density

The distribution of magnetic flux density shown in Figure 9 generated by the FEM with the transformer is in no-load condition by Magnetostatic solver. As seen in the Figure 9, magnetic field is uniformly distributed over the steel core. Thus, through the color shaded (magnetic field, B), it clearly reveals that the magnetic field distribution has a horizontal symmetry axis that passes through the middle of the transformer core limbs.

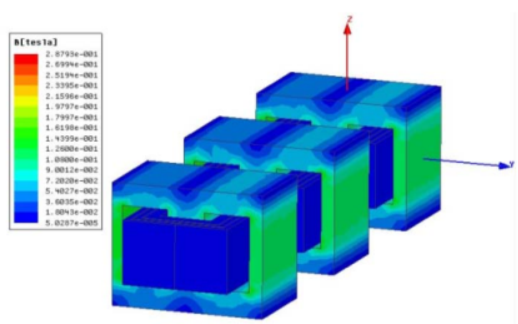


Figure 10. Magnetic field distribution of transformer model by FEM.

4.4. Result Output Waveform

Figure 11 and Figure 12 represent the results input and output voltage waveforms from Finite Element Method (FEM). It is clearly seen that the output is a balanced five-phase supply from a three-phase input. Individual output phases are shown along with their respective input voltages.

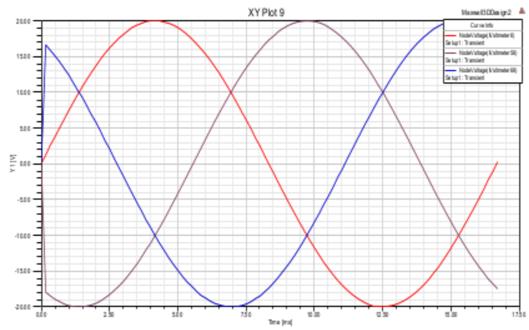


Figure 11. Three phase input from ANSYS Maxweel

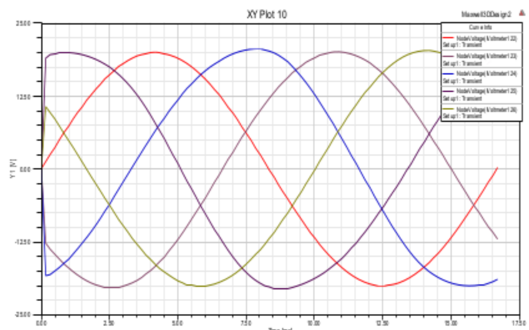


Figure 12. Balanced output of five phase transformer from ANSYS Maxweel

5. CONCLUSION

This paper deals with the contribution to develop a transient model of transformer coupled with external circuit. Thus, involving of identical actual transformer specification to transform the three-phase to a five-phase output supply using FEM. Extensive simulation clarify the ability of FEM to clearly visualize the model and pattern of electromagnetic characteristic of the transformer. The connection scheme and the phasor diagram along with the turn ratios were distinctly illustrated.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) and Ministry of Education (KPM) for sponsoring this research works under grant (FRGS/2/2013/TK02/UTEM/02/7). Correspondingly to ANSYS Maxwell software for the capabilities required towards the completion of this works.

REFERENCES

[1] Sunil Kumar J, Shalin J, PGV Suresh Kumar, Fikadu Wakijira, Development of Three phase to five phase Transformer using a novel technique, 2013; 4(3).

[2] N Monika, V Samhita, PV Swetha, B.Somashekar, Modelling And Simulation of Three-Phase To Five-Phase Transformation Using a Special Transformer Connection, 2013 3(5): 798–807.

[3] A Iqbal, S Moinuddin, MR Khan, SM Ahmed, H Abu-Rub, A Novel Three-Phase to Five-Phase Transformation Using a Special Transformer Connection, *IEEE Trans. Power Deliv.*, 2010; 25(3): 1637–1644.
[4] AS Abdel-Khalik, Z Shafik, a Elserougi, S Ahmed, a Massoud, A static three-phase to five-phase transformer based on Scott connection, *Electr. Power Syst. Res.*, 2014; 110: 84–93.
[5] K Lanka, T Kambhampati, B Kumar, M Kalyan, Three Phase to Five-Phase Transformation Using a Special Transformer Connection, I(Ii): 1–11.
[6] LS Goud, T Srivani, A Simulation of Three Phase to Multi Phase Transformation using a Special Transformer, 2013; 2(7): 351–357.
[7] Wang H, Member S, Butler KL. Distribution Transformers, 2001; 16(3): 422–428.
[8] Behjat V, Vahedi, Numerical modelling of transformers interturn faults and characterising the faulty transformer behaviour under various faults and operating conditions. *IET Electric Power Applications*, 2011; 5(5): 415.
[9] MSA Khiar, IS Chairul, Conditions from SFRA Measurement Results Transformers, 2012; 6–7.
[10] HT Jaya, A Review of Finite Element Method in Detecting Incipient Faults Occur in Power Transformer, 2–6.
[11] S Ruangsinchaiwanich, K Khongseephai, *Investigation of transformer performance by the finite element method*, Int. Conf. Electr. Mach. Syst., 2009; 1–6.
[12] HM Ahn, BJ Lee, SC Hahn, *An efficient investigation of coupled electromagnetic-thermal-fluid numerical model for temperature rise prediction of power transformer*, Int. Conf. Electr. Mach. Syst., 2011; 1–4.
[13] SC Bell, PS Bodger, *Power transformer design using magnetic circuit theory and finite element analysis-A comparison of techniques*, Australas. Univ. Power Eng. Conf., 2007; 1–6.
[14] S Liu, Z Liu, Oa Mohammed, FE-Based Modeling of Single-Phase Distribution Transformers With Winding Short Circuit Faults, *IEEE Trans. Magn.*, 2007; 43(4): 1841–1844.
[15] CF Scott, A Pioneer, Charles F. Scott, 1998; II: 6–8.
[16] MR Khan, SM Ahmed, Three-Phase to Seven-Phase Power, 2012; 27(3): 757–766.
[17] PS Georgilakis, Recursive genetic algorithm-finite element method technique for the solution of transformer manufacturing cost minimisation problem, *IET Electr. Power Appl.*, 2009; 3(6): 514.
[18] Yuxing Wang, Jie Pan, Ming Jin, Finite Element Modeling of the Vibration of a Power Transformer, The University of Western Australia, 2011.
[19] Hyun-Mo Ahn, Yeon-Ho Oh, Joong-Kyoung Kim, Jae-Sung Song, Sung-Chin Hahn, Experimental verification and finite element analysis of short-circuit electromagnetic force for dry-type transformer, *IEEE Trans. on Power Magnetics*, 2012; 486(2): 819-822.

Multiphase Transformer Modelling using Finite Element Method

ORIGINALITY REPORT

24%
SIMILARITY INDEX

MATCHED SOURCE

5 Guozhao Hu, Xixiu Wu, Fei Long, Shipu Wu. "Chapter 7 A 3D-Coupled Field-Circuit Model for Analyzing the Internal Short-Circuit Faults of Power Transformer", Springer Science and Business Media LLC, 2015
Crossref
51 words — 2%

★Guozhao Hu, Xixiu Wu, Fei Long, Shipu Wu. "Chapter 7 A 3D-Coupled Field-Circuit Model for Analyzing the Internal Short-Circuit Faults of Power Transformer", Springer Science and Business Media LLC, 2015
Crossref
2%

EXCLUDE QUOTES	OFF	EXCLUDE MATCHES	OFF
EXCLUDE BIBLIOGRAPHY	OFF		